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Screw-Propelled Robot for Detecting Grease Pipe

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Abstract

In the nuclear reactor containment building, a post-tension duct is filled with grease to protect the steel strand from corrosion. A potential issue arises if the grease leaks due to a duct break, as this could lead to corrosion of the steel strand, posing a safety risk to the building. Therefore, it is essential to proactively inspect and prevent grease leaks. However, the current inspection method is inefficient, as it requires the removal of both the grease and the steel strand for inspection. Additionally, alternative methods for inspecting post-tension dust have not been thoroughly researched. In this research paper, we introduce a novel approach by developing a screw-propelled robot designed to navigate through the grease-filled duct and directly detect grease leaks. Furthermore, we have created a test environment that closely simulates a real post-tension duct within a containment building. We conducted experiments to evaluate the feasibility of our robot's performance within the environment. The robot utilizes a twin screw mechanism to move both forward and backward within the grease duct, equipped with sensors to identify grease leakage and monitor strand corrosion.

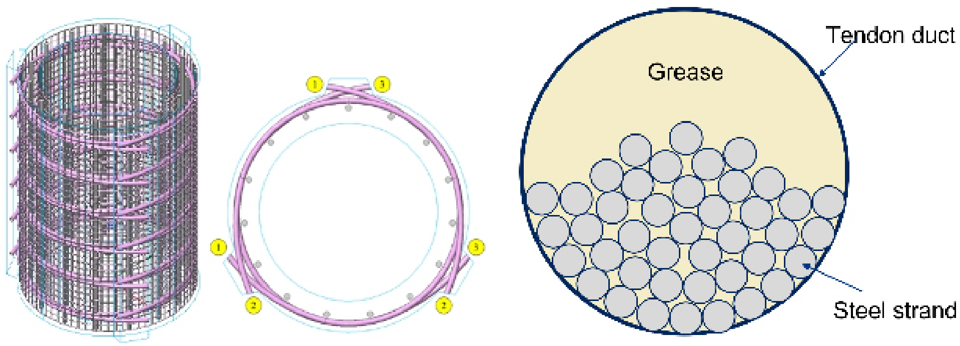
Keywords

Screw-propelled robot
Grease
Post-tension duct

1. Introduction

The nuclear reactor containment building employs a post-tension method within its exterior walls, as illustrated in **Figure 1** [1], to enhance the building's structural strength. The post-tension method involves inserting bundles of steel strands inside the duct and securing them under tension. This tension serves to offset any pressure that may occur within the building due to accidents, thereby preventing damage and increasing the safety of the structure. Within the containment building's post-tension ducts, grease is used to protect the steel strands from corrosion and damage caused by air, moisture, and other contaminants.

In the event of duct damage leading to grease leakage, the steel strands may corrode and jeopardize



(a) (b)

Figure 1. (a) Tendon duct locations in containment building; (b) cross-section of the tendon duct

the safety of the building. Indeed, issues related to grease leakage and subsequent steel strand corrosion have been observed in both domestic and international nuclear power plants, such as Units 3 and 4 of the Hanbit Nuclear Power Plant. Consequently, the methods for detecting grease leaks and steel strand corrosion have become crucial topics. However, the application of the post-tension method with grease filling within ducts is limited to nuclear reactor structures, resulting in a shortage of relevant research. Currently, the inspection method employed follows the American approach, which involves directly removing and subsequently reinstating the grease and steel strands within the duct. This method is inefficient as it requires significant time and cost, as it involves calculating the quantity of grease within the duct to determine the presence of grease leaks and voids, and visually inspecting the steel strands for corrosion.

In this paper, we have developed a screw-propelled robot capable of directly inspecting the grease-filled duct without removing the grease and steel strands. We have also created an environment simulating an actual post-tension duct to validate the feasibility of the robot's technology. This robot can move forward and backward within the grease duct, equipped with sensors that can detect grease voids and steel strand corrosion simultaneously. Consequently, it offers a more efficient inspection method compared to the traditional approach, reducing both the time and costs required for inspection.

2. Robot modeling

Conventional pipe robots typically employ wheels for propulsion, utilizing friction between the wheels and the inner wall of the pipe to move within it [3]. However, due to the unique environment where grease-filled ducts need to be navigated, the lubricating effect reduces friction, and the presence of grease leads to increased resistance. Consequently, the use of wheel-based propulsion methods is impractical. Furthermore, post-tension ducts, as depicted in **Figure 1**, have bundles of steel strands inside them, creating a space that is roughly conical in shape, with a raised central section. Therefore, to operate in the narrow space divided into left and right sections from a central point, the robot's design must accommodate these conditions.

To enable the robot to propel itself in such an environment without relying on friction and penetrate spaces filled with grease, we adopted the principle of a twin-screw extruder. Two screws rotate in opposite directions, digging into the grease and pushing it backward, thereby allowing the robot to progress within the grease-filled space. Additionally, we minimized the diameter of the screw cylinder while adjusting the pitch of the screws to ensure that the robot can effectively penetrate the grease-filled environment, as illustrated in **Figure 2**.

For the detection of grease voids and steel strand corrosion, sensor mounts were installed at the front of the robot, as shown in **Figure 3**. The grease void

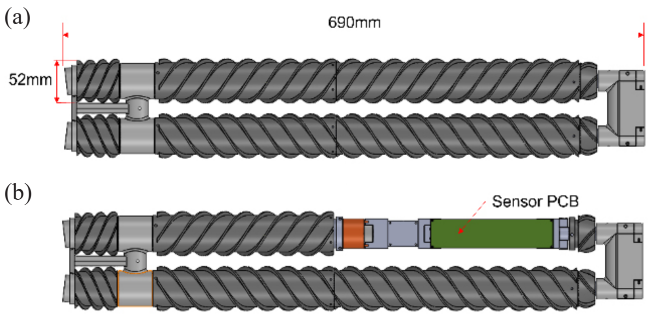


Figure 2. (a) Modeling of the screw-propelled robot; **(b)** printed circuit board (PCB) for sensor data communication

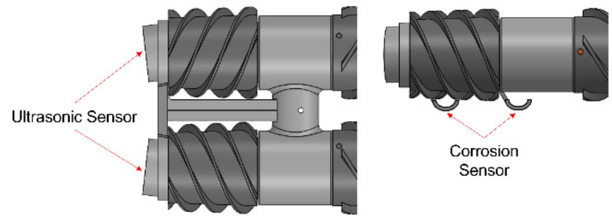


Figure 3. Modeling of the sensor mount

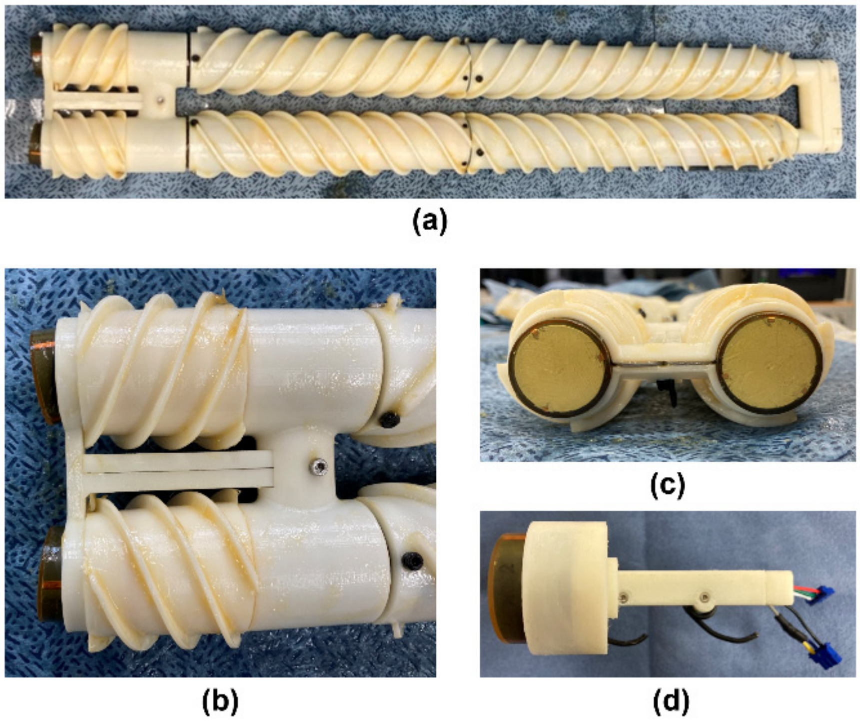


Figure 4. (a) Assembled screw-propelled robot; **(b)** sensor part of robot (top view); **(c)** sensor part of robot (front view); **(d)** sensor mount

detection sensor utilizes ultrasonic sensors to detect the presence of grease voids in front of the robot [4]. To maintain a certain angle between the transmitter and receiver modules of the ultrasonic sensors for proper signal reception, mounts were designed to ensure that the sensor surface faces in one direction.

The corrosion detection sensor employs two electrode probes that make contact with the steel strands and measure the potential difference between the two contact points [5]. Since both probes must remain in constant contact with the steel strands for the sensor to operate correctly, a housing was created between the two screws of the robot, and spring-mounted probes were installed in a row, as depicted in **Figure 4**. These probes maintain contact with the central steel strand of the duct, even in the presence of variations in strand arrangement during movement, thanks to their elasticity. After inspection, the probes are curved to allow for unobstructed robot movement during the extraction from the duct.

At the rear of the robot, a power/communication supply cable (hereby referred to as the Tether) is connected. The Tether supplies power to the robot and facilitates communication with the monitoring system, making it an essential component. However, since it is exposed directly to the grease, resistance may impede the robot's propulsion. This issue becomes more pronounced as the exposed area of the Tether in the grease increases. To address this, methods to reduce Tether resistance and provide rigidity to the Tether itself, along with pushing the Tether in coordination with the robot's propulsion, are under development as a means of assisting the robot's propulsion.

3. Modeling of experimental environment

The structure of the experimental environment is composed of a 6-meter-long, 150 mm inner diameter acrylic pipe, and 42 acrylic rods with a diameter of 15 mm, as depicted in **Figures 5–7**. In the actual environment, there is a 100-meter-long duct with an inner diameter of 152 mm, containing 42 steel strands with a diameter of 15.2 mm. The cross-sectional area not occupied by the acrylic rods in the experimental environment is approximately 10,724 mm^2, while the cross-sectional area in the actual environment is 12,717 mm^2. Although the experimental environment closely resembles the actual environment and presents slightly more challenging conditions, it was considered sufficient to validate the feasibility of the propulsion robot technology.

Furthermore, the temperature inside the post-tension duct within the nuclear reactor containment building's exterior walls is maintained at around 20°C [6]. To replicate this condition during the experiments, heating elements are installed outside the pipe to ensure that the grease temperature remains at 20°C throughout the testing process.

4. Propulsion experiment

Following the previously designed plan, we set up an experimental environment with a length of 6 meters and injected grease into the pipe to conduct propulsion experiments with the robot. As seen in **Figure 8**, the robot successfully penetrated and propelled itself within the grease-filled pipe. Subsequently, we measured the propulsion force using a load cell (**Figure 9**) and confirmed that the robot was capable of generating a maximum propulsion force of 14 kgf and a consistent force of 7 kgf during repeated experiments [7].

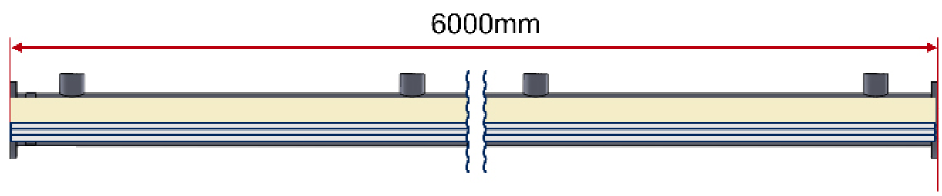


Figure 5. Modeling of the test environment

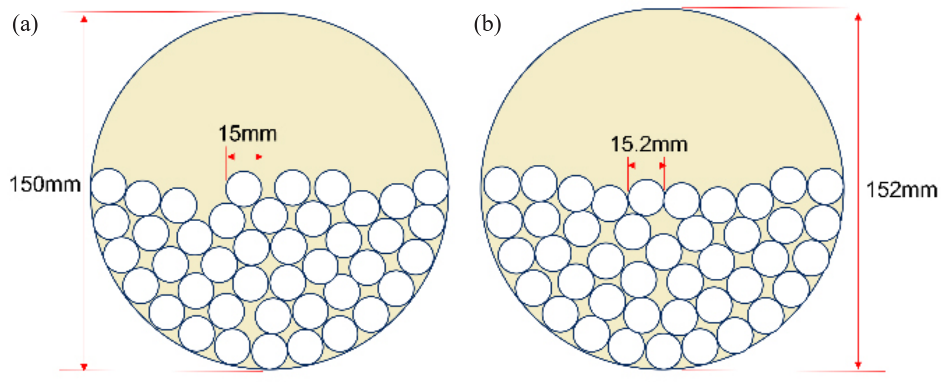


Figure 6. (a) Cross-section of the pipe for the test, inner diameter 150 mm, acryl rod 42 pcs; **(b)** cross-section of the real tendon duct, inner diameter 152 mm, steel strand 42 pcs

(a) (b)

Figure 7. (a) Test environment; **(b)** Cross section of the pipe for test

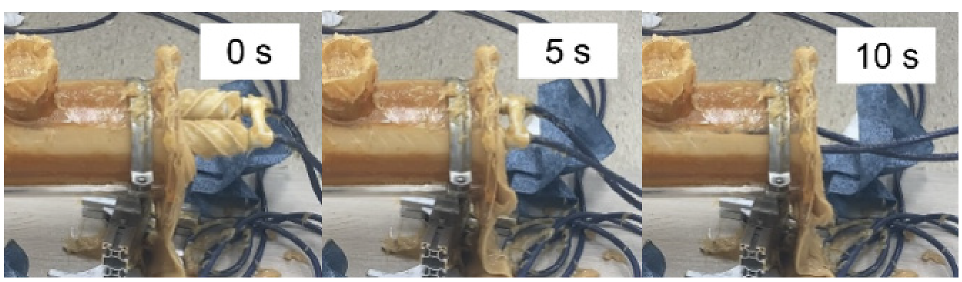


Figure 8. Robot propelling in grease

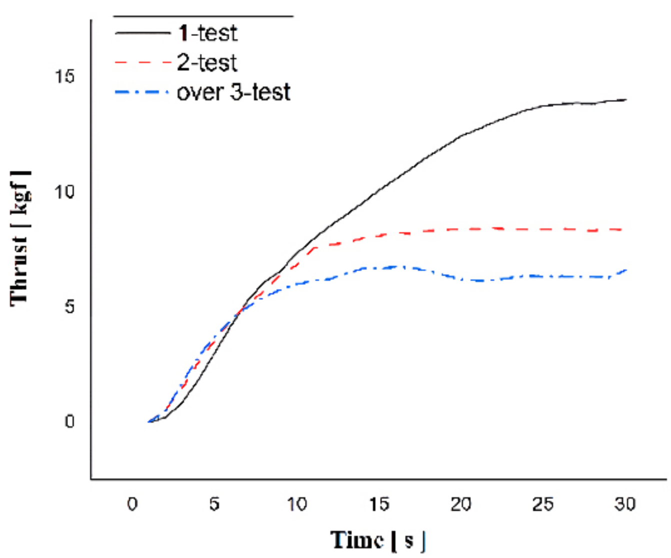


Figure 9. Propelling force of robot in grease

However, it was observed that after propelling for approximately 1 meter, the robot's speed decreased, eventually coming to a halt. This was attributed to the increasing resistance between the Tether connected to the robot and the grease, as anticipated during the robot modeling phase. As the robot propelled forward, this resistance gradually escalated, preventing the robot from further propulsion. Currently, both methods to reduce Tether resistance and utilize auxiliary propulsion force are under development, making it infeasible for practical application. To address this resistance issue, external assistance was necessary to provide additional propulsion force. We secured propulsion by winding a wire around the robot at a consistent speed, as shown in **Figure 10**. Using this wire-assisted method, we confirmed that the robot was able to progress normally within the 6-meter pipe, as demonstrated in **Figure 11**.

Furthermore, to validate the simultaneous operation between the robot's propulsion and sensor detection, we inserted structures inside the grease pipe to create voids (**Figure 12**). We also replaced the acrylic rods inside the pipe with steel strands containing corrosion zones to create a 1.5-meter experimental environment. In this setup, ultrasonic sensors and corrosion sensors operated concurrently with the rotation of the screws, allowing for the transmission of data (**Figure 13**).

5. Conclusion

In this paper, the developed screw-propelled robot equipped with sensors for internal inspection successfully demonstrated propulsion and inspection capabilities within a grease-filled pipe environment, similar to a post-tension duct. It independently generated propulsion forces exceeding 7 kgf, validating the feasibility of the screw-propelled robot technology for direct inspection of the interior of grease ducts. Up

Figure 10. Winch to pull robot

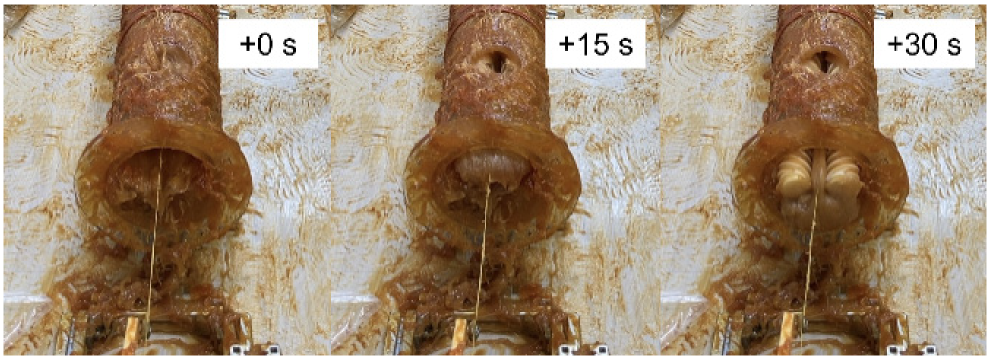


Figure 11. Robot passing through 6 m pipe, 15 sec interval

Figure 12. Sensor testing environment with grease void structure

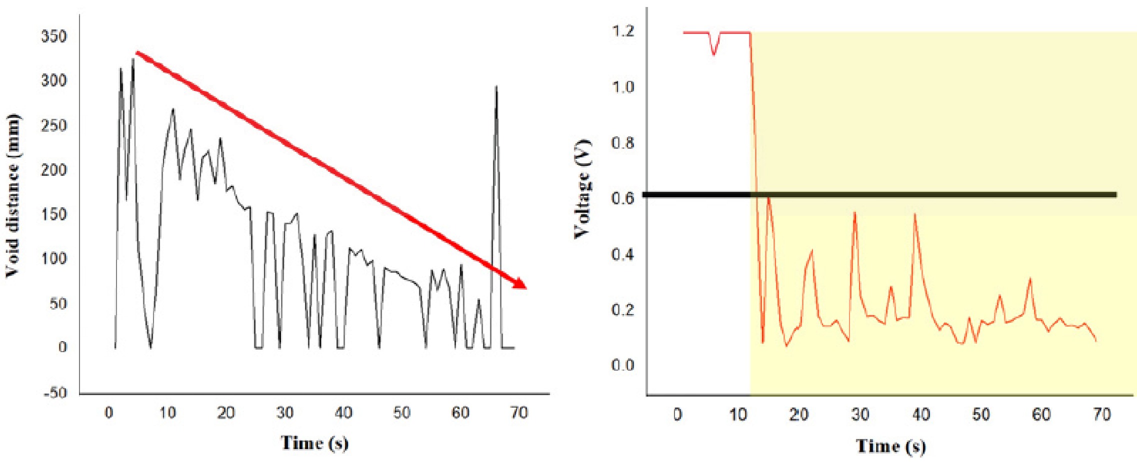


Figure 13. Sensor data collected during robot propelling

to this point, experiments were conducted under the assumption of a filled grease duct. However, in real-world scenarios, factors other than increased Tether resistance leading to insufficient propulsion force may contribute to a decrease in propulsion force. These factors can include a shortage of grease required for robot propulsion due to grease leaks. To address these challenges, auxiliary propulsion is necessary. Ongoing research aims to reduce Tether resistance and secure auxiliary propulsion force. While wire-assisted towing was used in this study to compensate for the reduction in propulsion force due to Tether resistance, it is not a feasible solution for practical application. Therefore, additional research will focus on securing auxiliary propulsion force by connecting additional propulsion modules at regular intervals, in addition to the ongoing Tether resistance reduction and auxiliary propulsion force research.

Disclosure statement

The authors declare no conflict of interest.

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